Fuel Consumption and NOx Trade-offs on a Port-Fuel-Injected SI Gasoline Engine Equipped with a Lean-NOx Trap

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Focus of Presentation

3 combustion features

Three Main Aspects:

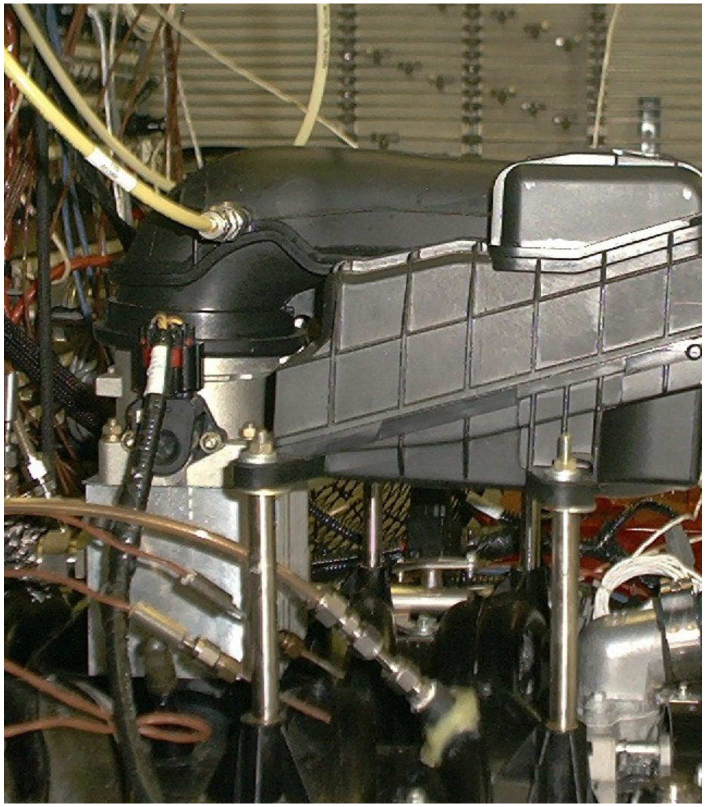
1. **Effects of Lean-burn, EGR, and deVCT on BSFC and BSNOx at 1200 rpm, 4 bar BMEP**
2. **NOx trap purge fuel requirements at several of the best BSFC/BSNOx points**
3. **Trade-offs between tailpipe NOx emissions and "effective" BSFC* (and implications for lean-burn engine operation in general)**

*$BSFC_{effective}$ = Cycle-weighted BSFC for lean operation (NOx storage) and rich operation (NOx trap purge)

Engine: 2005 5.4L 3V V-8* with:

- dual equal VCT (deVCT)
- non-production external EGR system (see below)

*Stein, et al., *The Combustion System of the Ford 5.4L 3-Valve Engine* Proc. 2003 Global Powertrain Congress, Vol. 24, Ann Arbor, MI Sept. 23-25, 2003



What's new?

- lean operation
- EGR system (non-production)
- aftertreatment (TWC+LNT)

But……

- 1200 rpm, 4 bar BMEP only
- 250 combinations of lean AF, cam retard, and % EGR

The Lean Challenge

5.4L PFI V-8 Engine @1200 rpm/4 bar BMEP

NOx

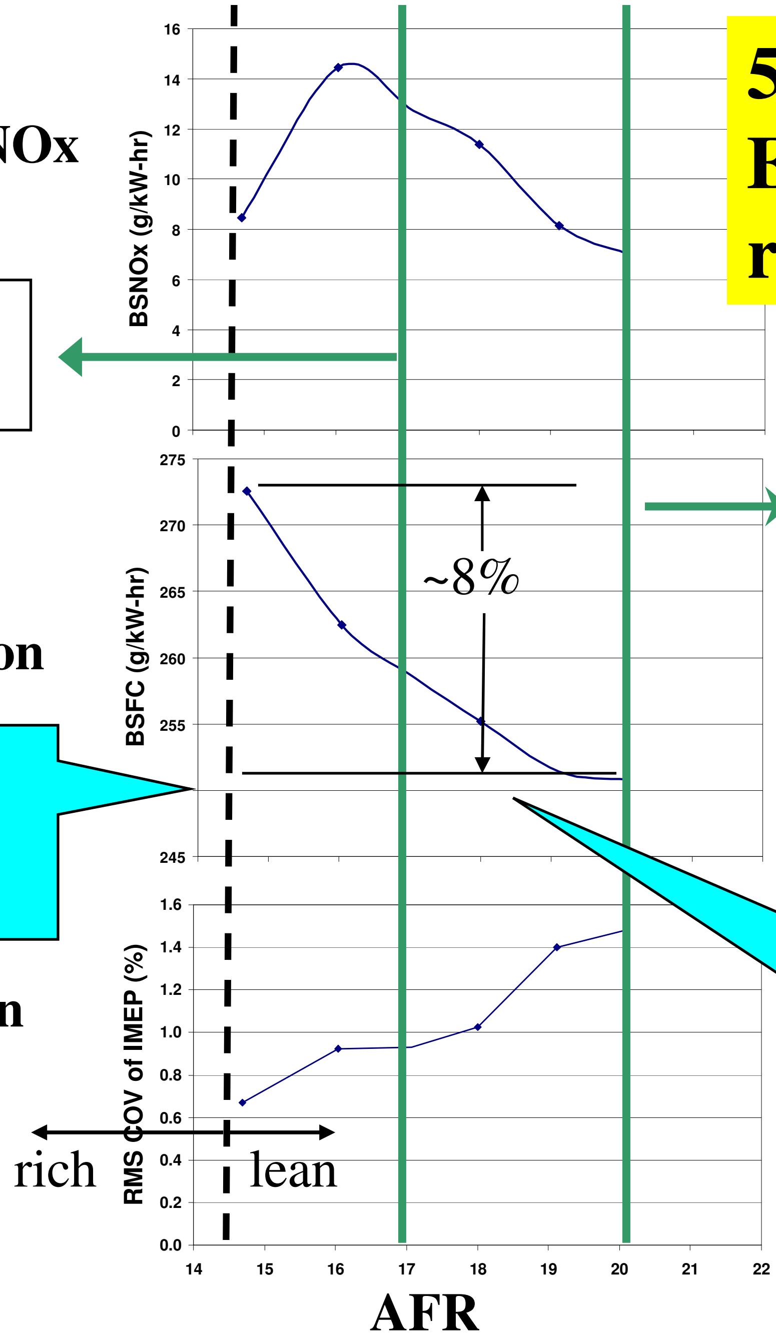
NOx & BSFC both too high

Fuel Consumption

Combustion becomes unstable

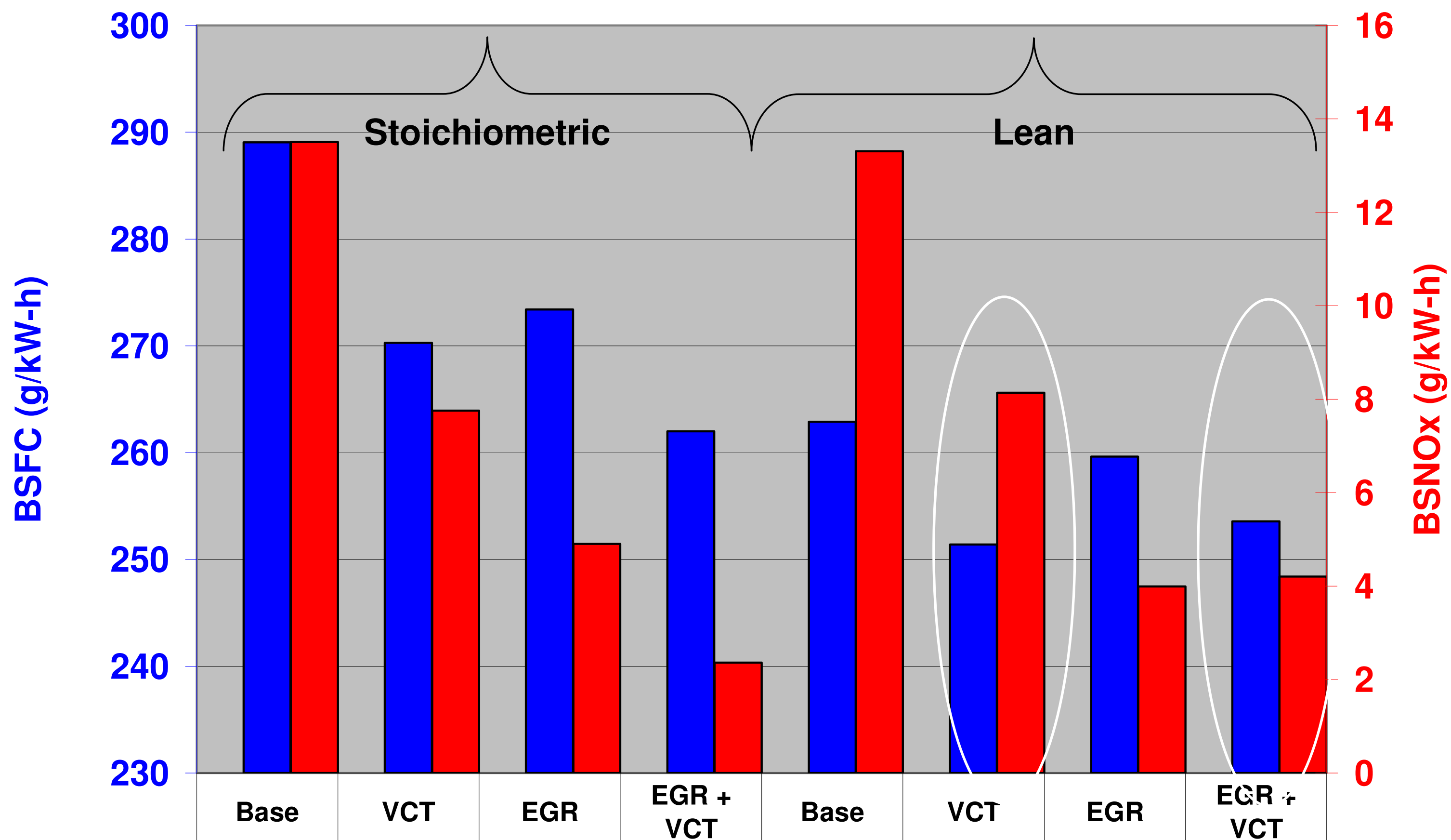
Gasoline lean-burn can default to stoich or rich conditions

Combustion Stability



Lean PFI has narrow operating range compared to stratified gasoline and diesel

BSFC vs BSNOx comparison for various combustion features (1200 rpm/4 bar)



AFR	14.7	14.7	14.7	14.7	20.1	19.1	20.2	17.1
CAM	0	45	0	40	0	40	0	30
EGR	0	0	15	17	0	0	10	17
COV	0.45	0.73	0.64	1.07	0.83	1.40	1.66	1.61

Fuel breakdown analysis

	Stoich	Stoich w/ deVCT	Stoich w/ EGR	Stoich w/ EGR w/ deVCT	Lean (20:1)	Lean + deVCT	17 AFR 30 CAM 16.7EGR
BSNOx (g/kW-h)	19.14	10.34	5.80	2.93	13.30	11.14	4.28
BSFC (g/kW-h)	287.3	273.0	274.2	262.1	261.1	253.2	253.9
% decrease vs. stoich (measured)		5.00	4.58	8.79	9.12	11.89	11.64
calculated % decrease in BSFC due to:							
➢ *PMEP*		4.54	1.89	6.37	1.69	5.88	6.28
➢ *Dilution*		0.45	2.58	2.84	6.90	5.62	5.05
➢ *HC*		0.45	-0.35	-0.29	-0.66	-0.43	-0.68
➢ *CO*		-0.93	0.35	-0.01	1.34	1.37	1.39
➢ *Combustion Phasing*		0.13	0.09	0.13	0.08	0.13	0.12
➢ *FMEP*		0.36	0.02	-0.25	-0.23	-0.67	-0.52

~ 3% BSFC benefit for best lean case vs best stoich case

How lean-burn helps fuel economy

- Decreases pumping losses (i.e. PMEP), but no incremental benefit over VCT + EGR
- Improves fuel conversion efficiency via the dilution (or "gamma") effect on the burned gas expansion process
  - $\eta_f = 1-(1/r_c^{\gamma-1})$ [where $\gamma = C_p/C_v$, and the greater mass of gas results in lower burned gas T and C_v and thus greater γ; also less heat transfer and dissociation]
  - Partial overlap with EGR and slight overlap with VCT
- Decreases CO/H_2 emissions (lost fuel)

Engine-Out Fuel Consumption & NOx Optimization

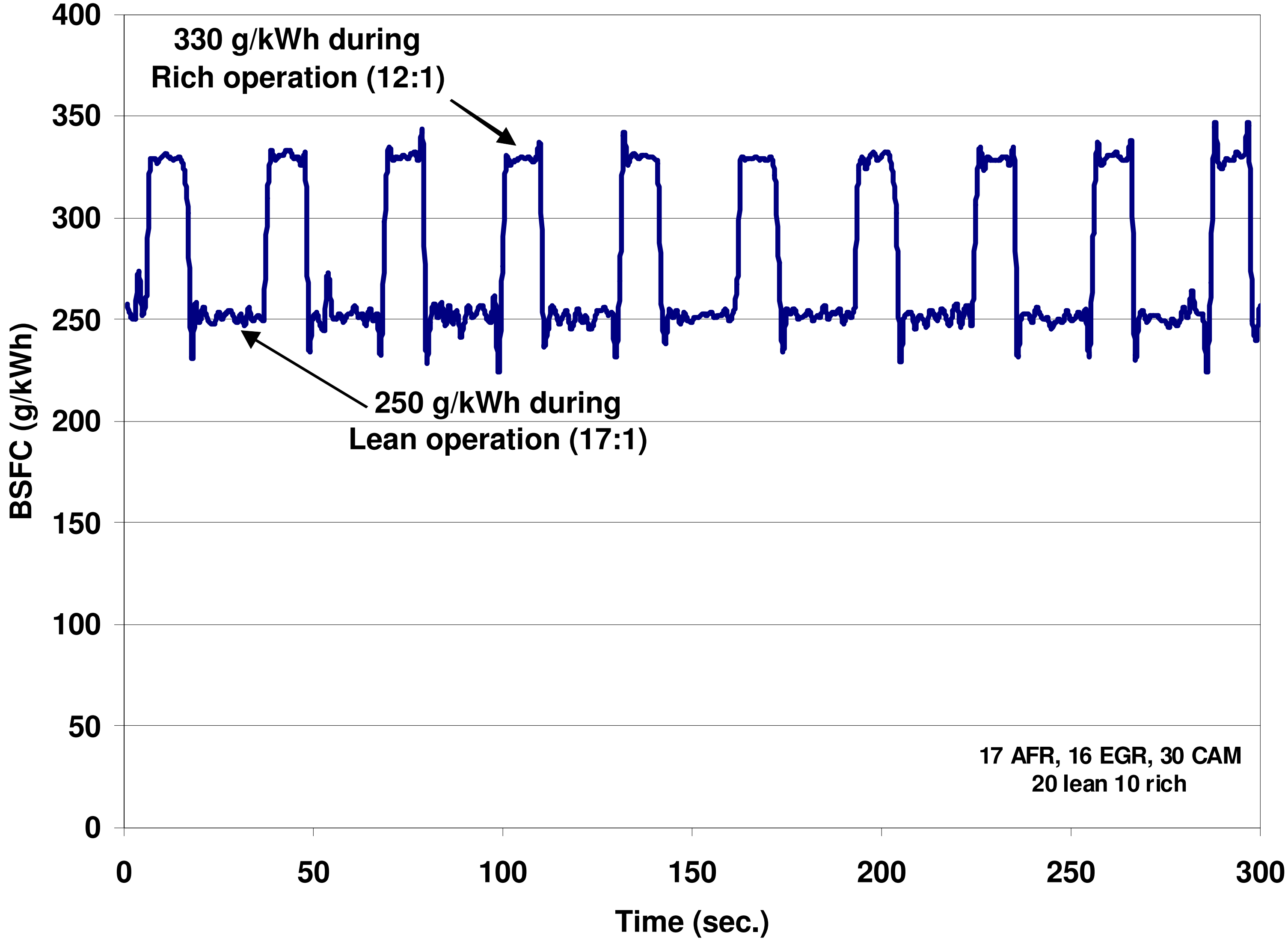
	AFR	CAM	EGR	BSNOx	BSFC	RMS COV IMEP
Stoich at Base Cam	14.66	0	0	13.50	289.1	0.45
Stoich at 45 CAM	14.69	45	0	7.76	270.3	0.73
Stoich + VCT + EGR	14.70	40	17	2.36	262.0	1.07
Lean only	20.05	0	0	13.31	262.9	0.83
Lean + VCT	19.12	40	0	8.14	251.4	1.40
Lean + EGR	20.19	0	10	3.99	259.6	1.66
Lean + EGR + VCT	17.05	30	17	4.20	253.5	1.61

- Best BSFC is obtained with Lean & VCT only.
- Adding EGR greatly reduces NOx but at the expense of higher BSFC than with best Lean+VCT case.
- Best engine operating condition can only be determined based on <u>tailpipe</u> emissions and fuel consumption.

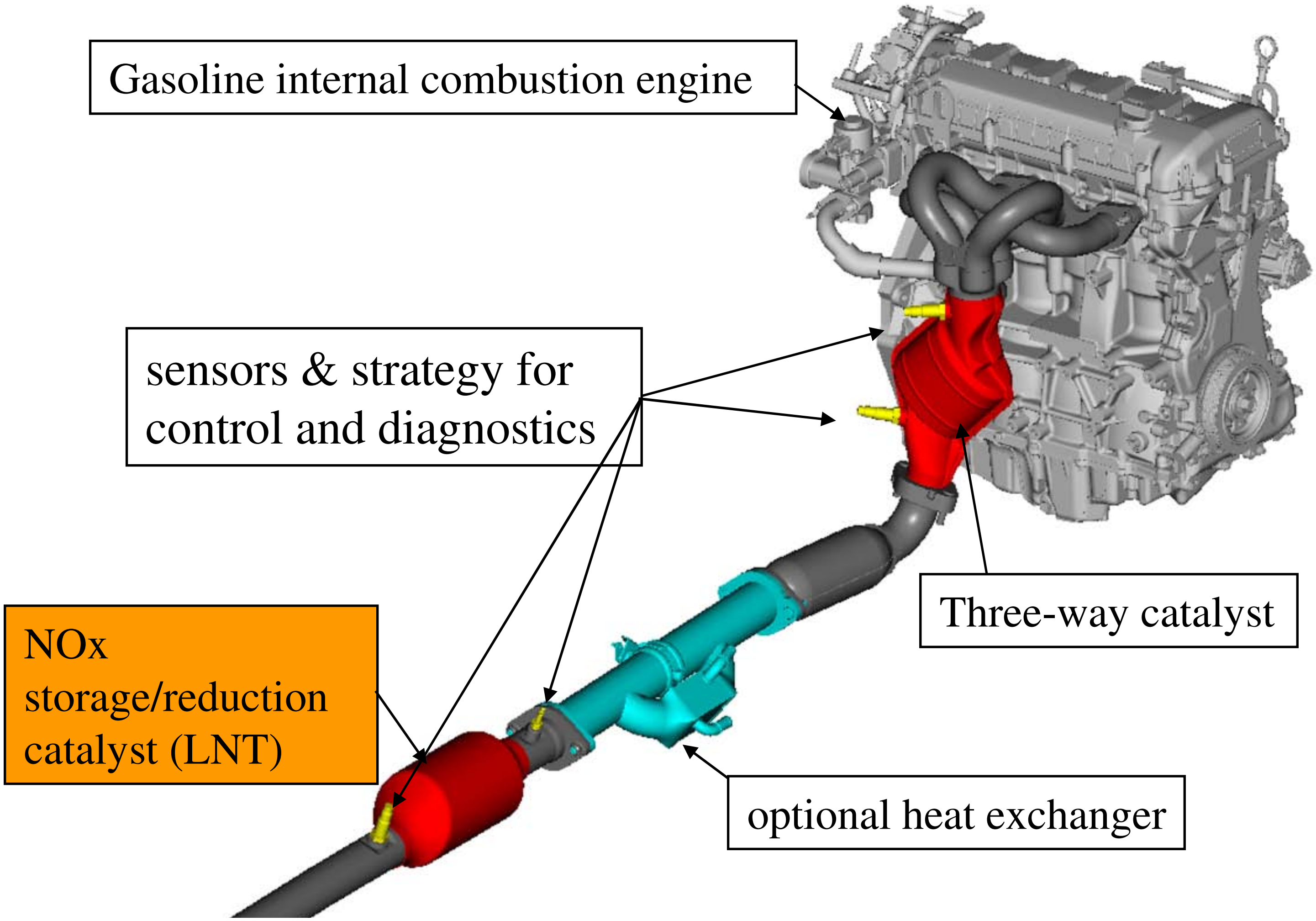
Part 2: LNT Impact on NOx Tailpipe Emissions and $BSFC_{effective}$

- NOx tailpipe emissions:
  - LNT needs low engine-out NOx to operate with high efficiency
- $BSFC_{effective}$:
  - cycle-weighted BSFC for lean storage and rich purge
- Trade-off between low BSFC and low TP NOx

Lean-rich duty cycle for LNT operation



The Modern IC Engine with Lean-Burn Aftertreatment System – a rich integration of chemical, mechanical and controls engineering



Lean NO_x Traps

Like TWC, washcoat of LNT contains

- PGM (Pt, Rh, optional Pd)
- Al_2O_3, ceria for OSC, stabilizers

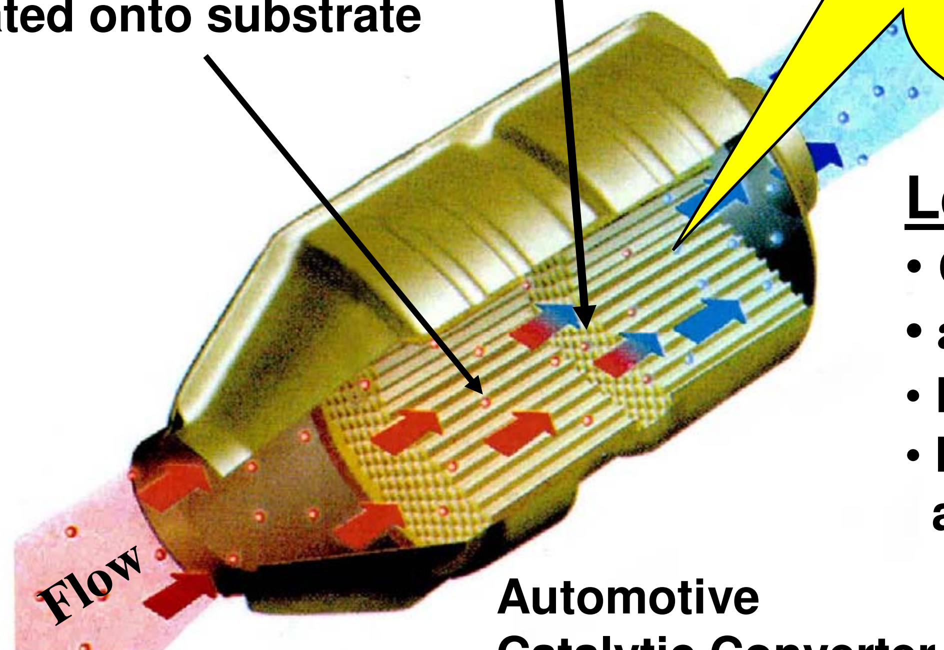
LNT also contains high levels of NO_x storage materials

-Alkaline-earth metals (Ba, Mg)

-Alkali metals (K, Cs, Na)

Ceramic substrates (cordierite)
400 cells/sq inch

Washcoat – a thin layer coated onto substrate

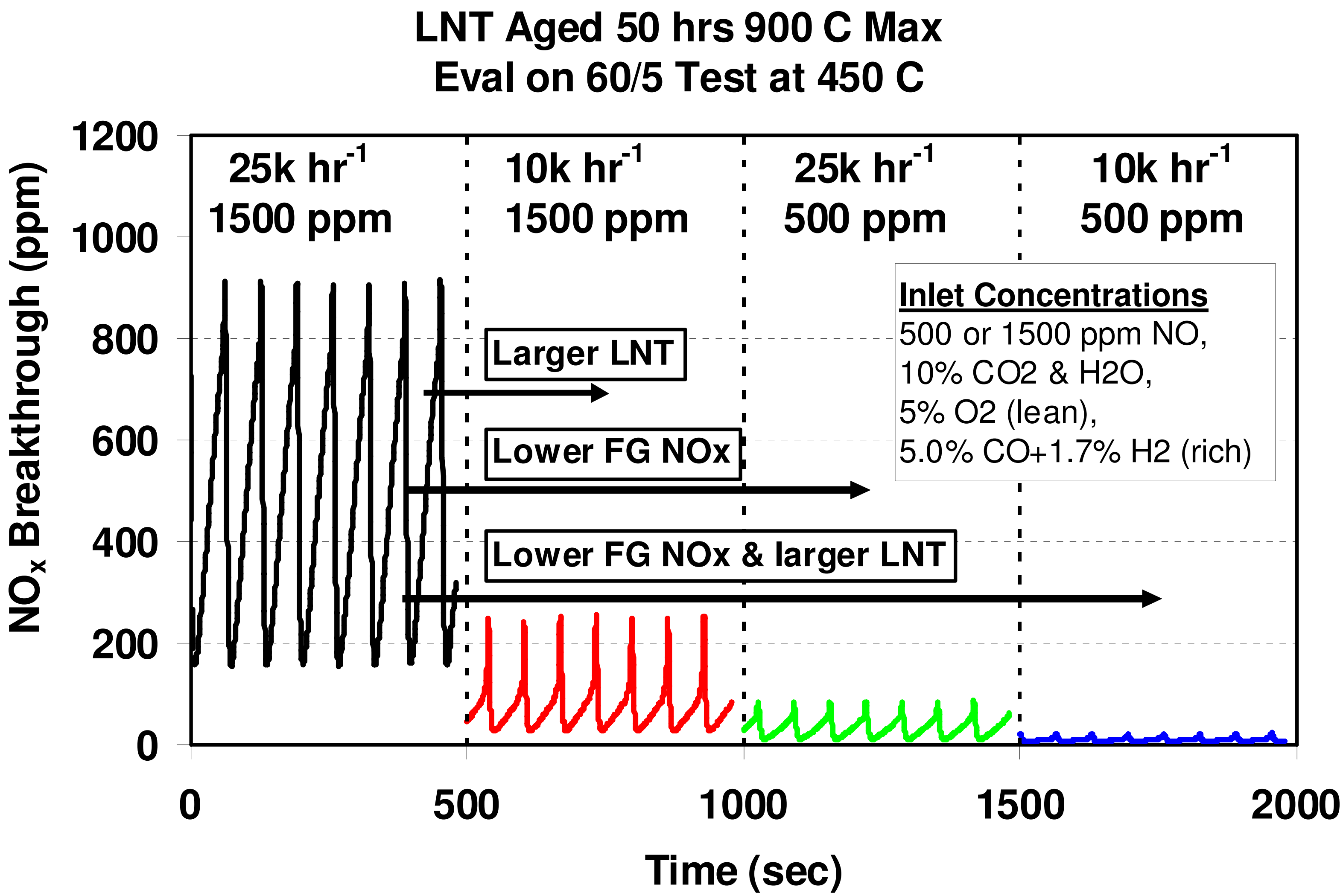


Automotive Catalytic Converter (TWC or LNT)

Lean NOx Traps

- Convert HC, CO, & NO_x at $\lambda=1$
- at $\lambda>1$ convert HC & CO, store NO_x
- Reduce stored NO_x to N_2 at $\lambda < 1$
- NO_x storage performance not as durable as TWC (800°C max)

Effect of NO_x Concentration & Flow Rate (SV) – Lab Data



Low feedgas NO_x and large LNT volumes will be vital for achieving very low NO_x emissions

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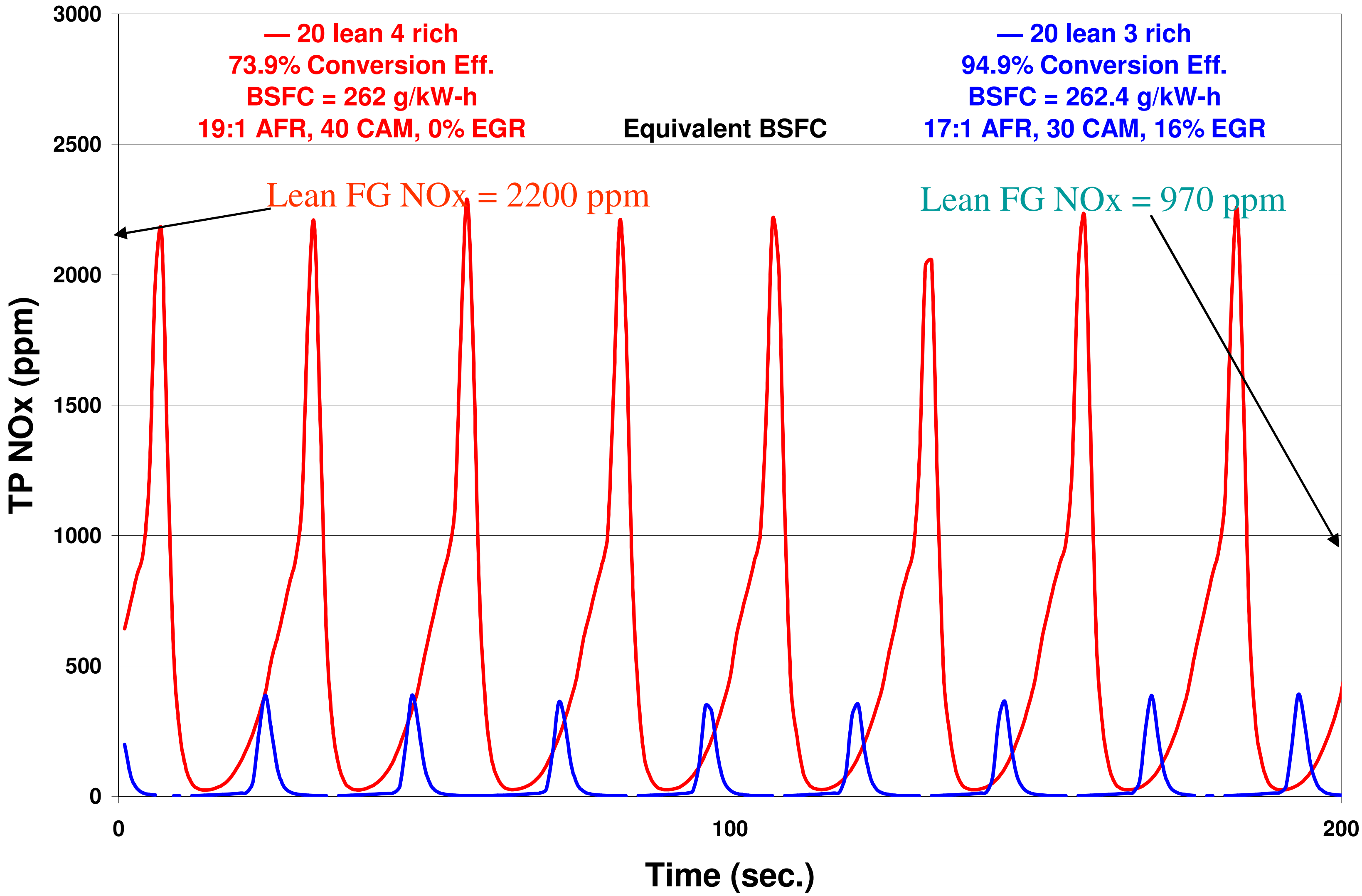
Tailpipe Fuel Consumption & NOx Optimization

Lean Purge (Matching Effective BSFC)

					BSFC (effective)	TP Nox (ppm)	
20 sec lean							
Lean + VCT	19.12	40	0	8.69	262.00	523.49	4s R
Lean + EGR + VCT	17.05	30	17	3.66	262.44	46.47	3s R
30 sec lean							
Lean + VCT	19.12	40	0	9.49	257.28	709.52	3s R
Lean + EGR + VCT	17.05	30	17	3.99	257.08	68.32	2s R

Tailpipe Comparison: Best NOx & Best BSFC Cases

Comparison carried out at equivalent effective BSFC



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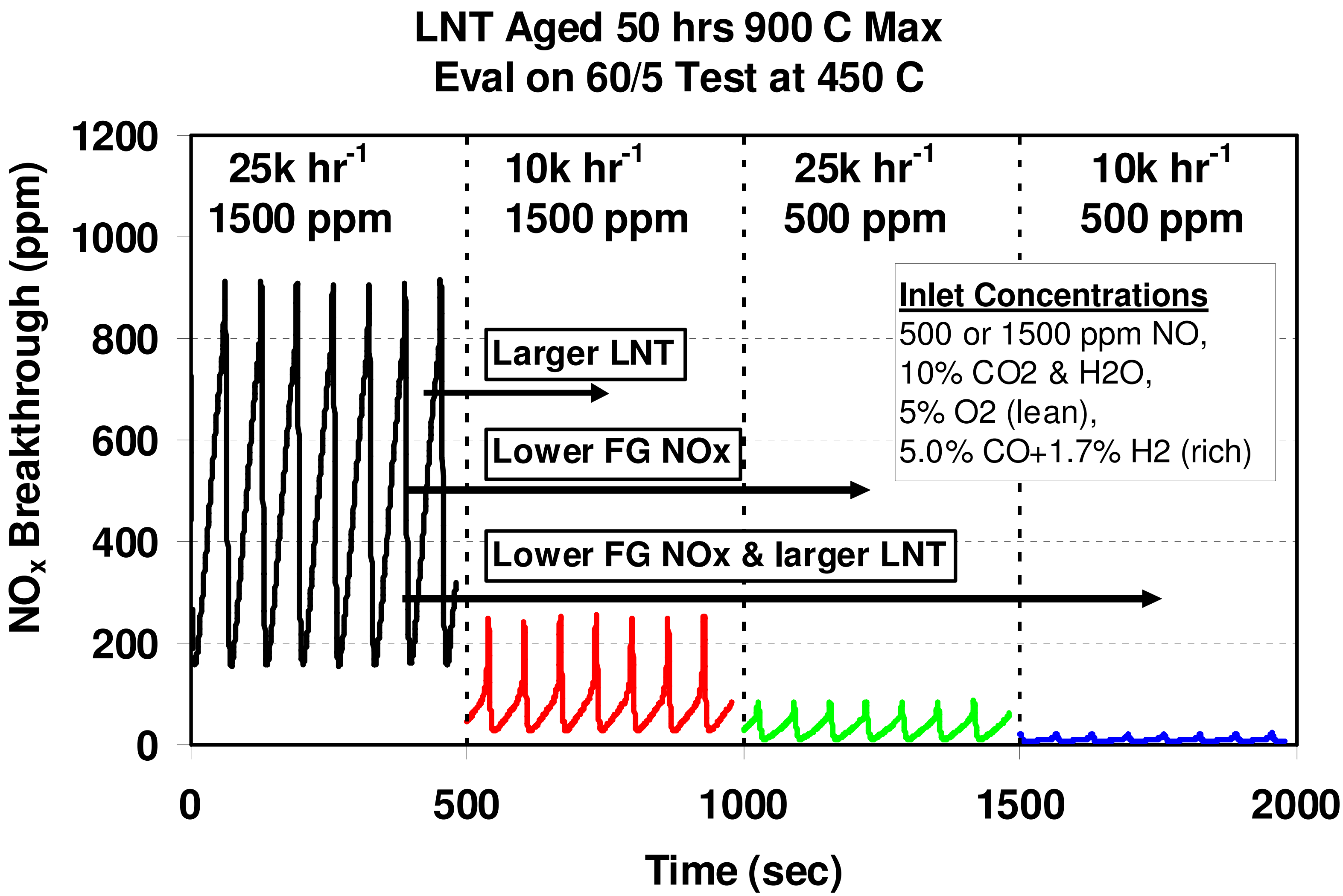

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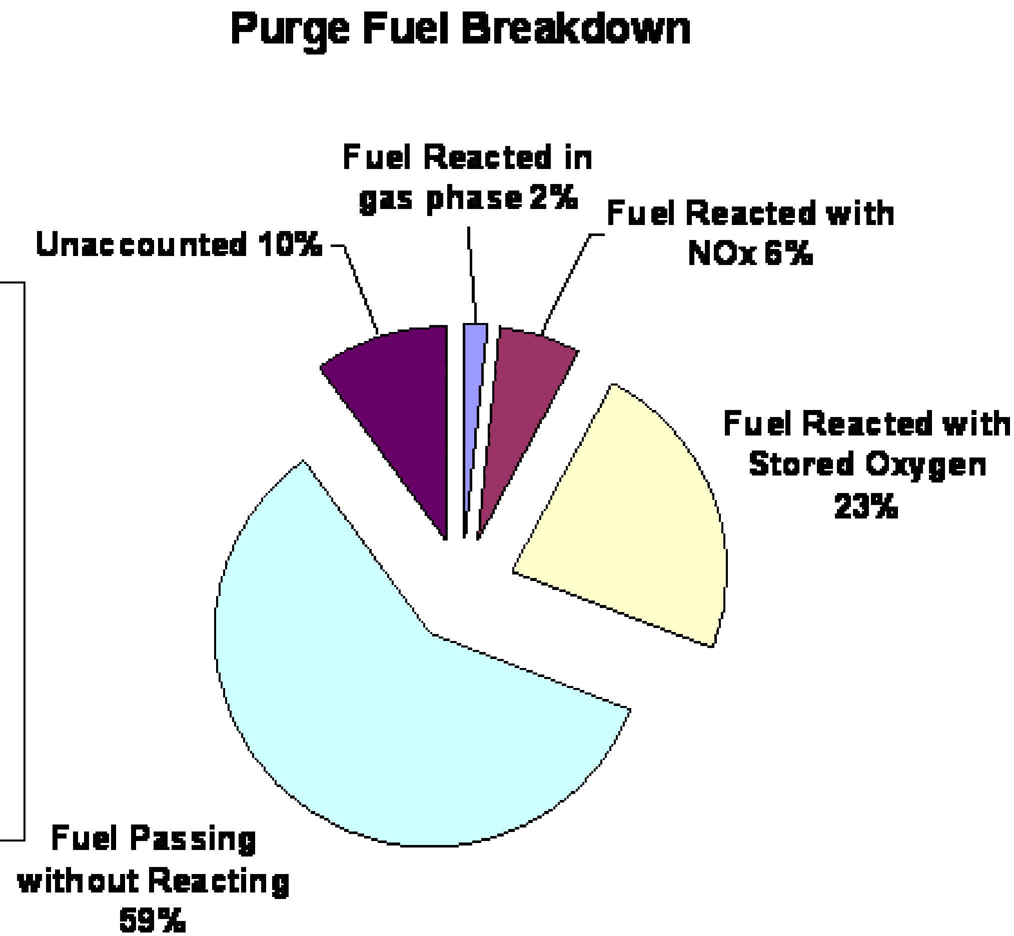
Purge fuel breakdown analysis

- Purge not efficient
- Not optimized (L→R step change)
- Richer purge λ best at higher T (Theis, et al. SAE 2003-01-1159)



Summary

- Lean-burn improves PFI fuel economy by ~3% relative to best stoichiometric VCT/EGR conditions, when used in combination with VCT&EGR.
- The benefit of lean-burn is largely due to improved fuel combustion efficiency owing to dilution.
- Both VCT and (especially) EGR reduce BSNOX, but the extra fuel required to purge a NOx trap gives back virtually all of the BSFC benefit of lean-burn.
- Successful implementation of lean-burn at low emission standards may require:
  - Engine-out NOx reduction with VCT and EGR
  - Alternative to LNT for NOx control (urea-SCR; LNT+in-situSCR)
  - New combustion modes (DI stratified or homogeneous lean, HCCI, PCCI) for ultra-low BSNOx
  - Engine operation in a fixed or narrow speed-torque range

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